Half-Massive Ceramics for Antenna Downsizing: Improvement of a Smart Magneto-Dielectric Material with Matching Permeability and Permittivity, and with Enhanced Low-Loss Frequency Range

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Abstract— **Complex permeability and permittivity of $Ni_{0.5}Zn_{0.3}Co_{0.2}Fe_{1.98}O_{4-x}$ half-ceramic ferrites (porosity ~50%), obtained from various annealing temperature T_A (500°C, 800°C, 900°C), are measured and compared. Their characteristic impedance Z, magnetic and dielectric loss tangents are presented. Bandwidth BW and radiation efficiency η values of patch antennas are obtained through numerical simulations and compact formulations. The value of the annealing temperature used for the substrates determines those of BW and η. BW and η are themselves used as criteria to decide which one among the various substrates is proper to be used at given frequency. It is concluded that whereas the sample annealed at 500°C is far to meet the required properties in reason of detrimental magnetic losses, the half massive ceramics got after annealing at T_A=800°C and 900°C show appropriate performances for further applications. The electromagnetic properties of half ceramics materials sound to be very competitive at frequencies up to 0.8GHz.**

Index Terms— **half-massive ceramics, magnetodielectric materials, antenna, miniaturization.**

I. INTRODUCTION

Miniaturization of electronic devices for mobile communication has led to increasing demands for the reduction of antenna dimensions, so that antenna downsizing is one of today's most important challenges for antenna designers [1]. The use of high-permittivity substrates allowed size reduction, but causes a considerable decrease in antenna efficiency and bandwidth [2]–[4]. For applications in the low-UHF frequency band (300-862 MHz), the use of magneto-dielectric substrates is expected to overcome these limitations by offering larger bandwidths and improved efficiency [5]–[9]. Indeed it has been shown [10] that, although the permittivity (ε') increases the impact of losses, as well as the stored energy, the permeability (μ') plays the opposite role by decreasing them. As a consequence, the negative impact of ε' on radiation efficiency (η) and bandwidth (BW) is counterbalanced by the positive impact of μ'. This was expressed through relations (1) and (2), derived for lossy magnetodielectric materials [10].

$$BW = \frac{1}{\sqrt{2}}\left(240\frac{d}{W}G_r\sqrt{\frac{\mu}{\varepsilon}} + tan\delta_\varepsilon + tan\delta_\mu\right) \quad (1)$$

$$\eta = \left(1 + \frac{tan\delta_\varepsilon + tan\delta_\mu}{240G_r}\frac{W}{d}\sqrt{\frac{\varepsilon}{\mu}}\right)^{-1} \quad (2)$$

The interesting point in these relations is that, unlike previous works, they take both magnetic and dielectric losses into account. Moreover, if loaded with magnetodielectric material antenna's dimensions can be reduced, theoretically, by a miniaturization factor n ($n=\sqrt{\varepsilon'\mu'}$ is the refractive index) while its electrical dimension remains unchanged [6]. The magnetodielectric materials should also present a characteristic impedance Z ($Z=Z_0\sqrt{\mu'/\varepsilon'}$, where Z_0 is free space impedance) close to that of free space, that requires matching μ' and ε'. Spinel ferrites, which have ε'>1 and μ'>1, together with low loss tangents (both dielectric and magnetic), are among the best candidates for antenna downsizing [11-15] . However most of the recent published studies focus on bulk ferrites, that show detrimental magnetic losses at frequencies higher than 300MHz, thereby limiting at frequencies lower than 300MHz their possible applications: recent work [13] report for a NiZnCo ferrite the following values: $tg\delta_\mu$=0.09, 0.5, 1.47 at frequencies f=0.2, 0.5, 1 GHz respectively. The sintering process that is commonly used to obtain dense ferrite substrates involves elevated sintering temperature (usually about 1100°-1200°C) [14], [15]. The grain growth to which this procedure leads is associated with a multi-domain magnetic grain structure, which ensured high permeability values. Then, however, undesirable magnetic losses associated with domain-wall bulging remain high from the quasistatic frequencies until several 100 MHz. In contrast, it has been shown that magnetodielectric materials in porous or composite forms, with moderate magnetic losses and low dielectric losses, have potential applications in antenna miniaturisation up to 700 MH [11, 18-19]. With the aim of avoiding low frequency losses we first suggested using porous (i.e., half-massive) ferrite ceramics, got from low annealing temperature and in which the grain size is small enough [11], [18]–[21]. Both porosity, that is a measure of the void space in a material, and concentration of cations Fe^{2+} in the ferrite chemical composition, have a strong influence on permeability and permeability. An experimental process that allows to obtain such half-massive ferrite was detailed elsewhere [13], [22]. The magnetic phase of the so got porous nanostructured material is constituted by nanograins of ferrite. It was also demonstrated that μ and ε are greatly sensitive to many parameters, and first of all to the annealing temperature T_A applied during material heat treatment. Actually, the value of T_A drives both Fe^{2+} and Fe^{3+} iron cations concentrations and the material porosity, to which μ and ε strongly depend. Typically, when T_A>1050°C the obtained ceramic is densified at a rate closed to 100%, and Fe^{2+} concentration is close to zero. Whereas when T_A<900°C, the material shows porosity close to 50%. Obviously, to increase T_A may involve variations of electromagnetic properties. When T_A changes from 800°C to 900°C, the variations in μ and ε might be attributed, for a very large part, to the decrease of the rate Fe^{2+}/Fe^{3+}, and, but only for a few part, to the limited decrease of the porosity fraction value (that remains about 50% for T_A=800°C as for T_A=900°C) [13]. The upper limit for frequency applications of ferromagnetic materials is fixed by the ferromagnetic resonance frequency F_R (The observed maximum of μ" in the μ"-f curve obtained on polycrystalline materials, accords with the resonance frequency; this feature defined the ferrimagnetic resonance F_R [23]). There is a great increase in magnetic losses and a decrease in permeability even only slightly below F_R. Furthermore, it should be noted that antennas then need to be used at frequency values much lower than F_R. As stated by Snoëk's law [24], F_R and the static permeability μ_S are related to each other: the higher the static permeability μ_S, the lower the spin resonance frequency F_R. It is written $(\mu_S-1).F_R=2/3\,\bar{\gamma}\,M_S$, where M_S is the magnetization at saturation and $\bar{\gamma}$ is the gyromagnetic ratio ($\bar{\gamma}$ =35.185 MHz/kA.m^{-1}). Snoëk's law is useful for estimating the microwave performances of a bulk polycrystalline material. Then it can be seen that μ_S and F_R cannot be as high as possible at the same time. Therefore the electromagnetic properties (including permeability μ=μ'–jμ", permittivity ε=ε'–jε", spin resonance frequency F_R and static permeability μ_S, miniaturization factor, reduced impedance) of half-massive ferrites can be easily tailored by choosing the appropriate temperature T_A. On the basis of our previous results the composition $Ni_{0.5}Zn_{0.3}Co_{0.2}Fe_{1.98}O_{4-x}$ was selected for this study, and annealing temperatures were 500°C, 800°C, 900°C. The abilities of the obtained materials to be used as magnetodielectric substrate up to 1GHz are compared together, by computing radiation efficiencies and bandwidth of patch antennas.

II. ELECTROMAGNETIC PERFORMANCES OF HALF-MASSIVE $Ni_{0.5}Zn_{0.3}Co_{0.2}Fe_{1.98}O_4$ FERRITE CERAMICS

Torroidal samples were obtained from nanosized ferrite particles (the particles mean size was equal to 12nm) by moulding before heat treatment. The experimental set up for measuring the complex dielectric constant and the complex permeability constant in the frequency range from 0.1-6GHz consisted of a coaxial transmission line (APC 7 standard), and a HP 8753S network analyzer. The method used was based on the measurements of the scattering parameters of a torroidal sample placed into the coaxial line. Dielectric permittivity and magnetic permeability were derived using the transmission/reflection method based on the algorithms of Nicolson, Ross, and Weir [25].

The complex permeability dispersion of the ferrite annealed at different temperature is shown in Fig.1. Permeability reveals the degree of magnetization that a material obtains in answer of an applied magnetic field. The complex permeability of ferrite may be related to two different mechanisms: the spin rotational magnetization, and the domain wall motion. The later mechanism, to which undesired high losses are attached since the quasi-static range, arises when the grain size is larger than a certain critical size. In order to avoid this detrimental domain wall contribution to the permeability, grain size should be kept below the critical size by using moderate annealing temperature. As a counterpart, the permeability value, when originating from spin rotation only, cannot reach very high values. In the present study, the fairly low value of permeability is attributed: first to the rotational contributions to magnetization in the nanoferrites, and second to the porous nature of the samples. Permittivity is determined by the ability of a material to polarize in response to an electric field. Because of their porous structure, the dielectric constant of the half-massive ferrite (Fig. 3) is quite low (in the range 5-7) as compared to ε'~16 for usual dense ferrites [26]. It should be underlined that both permeability and the permittivity show noticeable constant values in an unusual wide range of frequency starting from 0.1GHz up to 1GHz (inset in Fig. 1, and Fig.3).

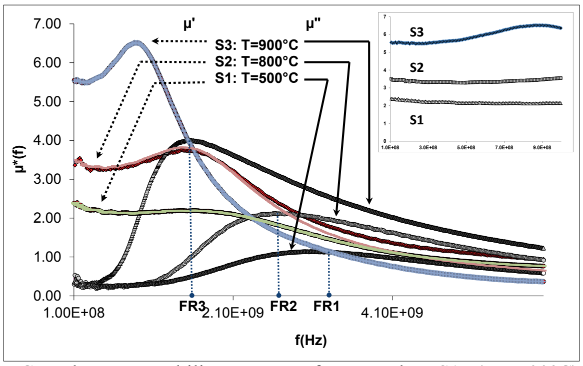

Fig.1. Complex permeability spectra for samples S1 (T_A=500°C), S2 (T_A=800°C), S3 (T_A=900°C) over the frequency range 0.1-6 GHz. Inset: focus on the real permeability over the frequency range 0.2-1 GHz

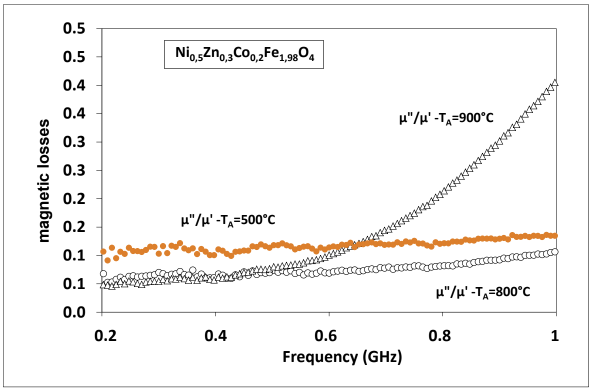

Fig.2. Magnetic loss tangent (μ"/μ') for samples S1 (T_A=500°C), S2 (T_A=800°C), S3 (T_A=900°C) over the frequency range 0.1-1 GHz.

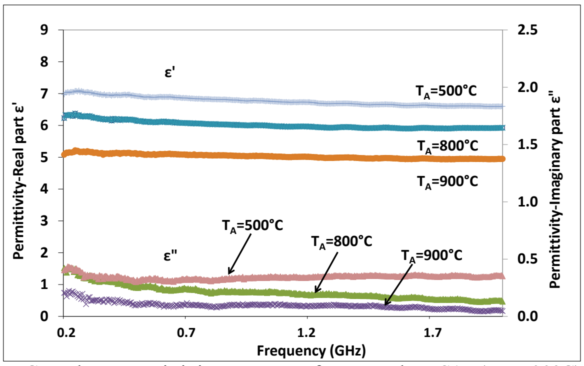

Fig.3. Complex permittivity spectra for samples S1 (T_A=500°C), S2 (T_A=800°C), S3 (T_A=900°C) over the frequency range 0.1-6 GHz.

This is an interesting feature, that is related to the uncomplete sintering of the ferrites samples Figures 4a-4c show, at given frequencies (f=0.4GHz, 0.8GHz, 1GHz), the values of μ and tgδ$_μ$, ε and tgδ$_ε$, and the overall losses tgδ$_μ$+tgδ$_ε$. Owing to its poor electromagnetic properties (low permeability, high dielectric and magnetic losses), sample S1 will be no more considered in the following.

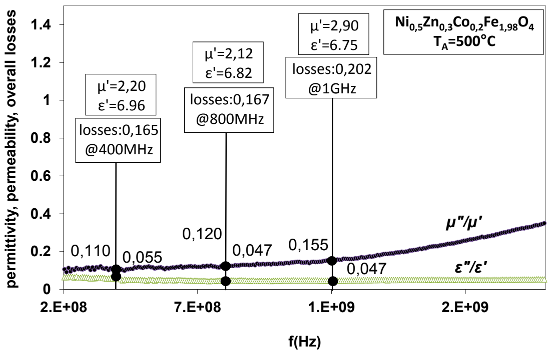

Fig.4a. Permeability, permittivity, magnetic losses, dielectric losses, and overall losses at given frequencies for sample S1 (T_A=500°C).

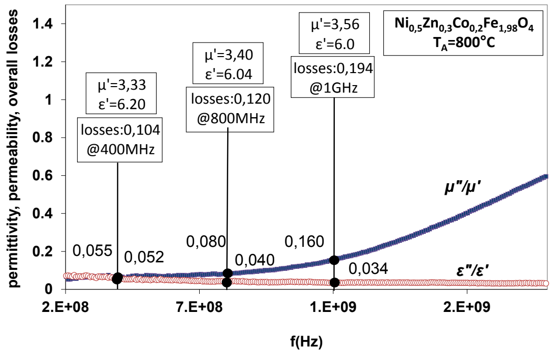

Fig.4b. Permeability, permittivity, magnetic losses, dielectric losses, and overall losses at given frequencies for sample S2 (T_A=800°C).

III. PATCH ANTENNA PERFORMANCES

Tables I and II show values of the miniaturization factor (n) and of the reduced impedance (Z/Z_0) at given frequencies, for the samples S2 and S3. For the sample annealed at T=900°C, considering the range of frequency up to 0.4-0.5GHz, reduced impedance is close to unity, the miniaturizing factor is constant (with a mean value ~5.6) and the overall loss tangent value remains moderate. Whereas beyond 0.4-0.5GHz, and up to 1GHz, the preferred annealing temperature should be T=800°C. For a more detailed discussion, the example of a square patch antenna (width *W)* printed over lossy magnetodielectric materials, (thickness d=3mm) is considered in the following.

The width *W* of the patch is obtained from the relationship :

$$W = \frac{\lambda_g}{2} = \frac{\lambda_0}{2n} = \frac{c}{2nF_0} \qquad (3)$$

Where c=3.10^{8}m/s represents the velocity of light, n the miniaturization factor and F_0, the operating frequency (0.4, 0.8, or 1GHz).

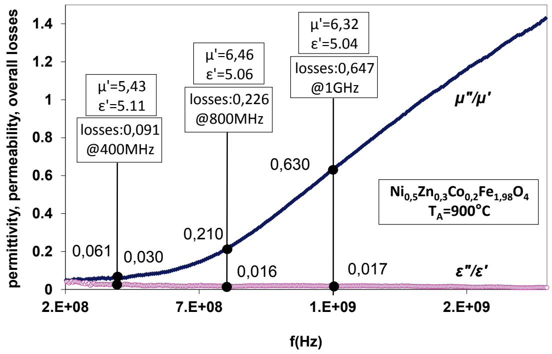

Fig.4c. Permeability, permittivity, magnetic losses, dielectric losses, and overall losses at given frequencies for sample S3 (T_A=900°C).

Tables I and II also provide calculated values of bandwidth and radiation efficiency, obtained from formulas (1) and (2), at given frequencies (0.4, 0.8, 1GHz). The classical trade-off between radiation efficiency and bandwidth is observed: it is not possible to get high values for both of them at the same time. As an example, let us consider a patch antenna intended to be used at f=0.4GHz. Because at this frequency the reduced impedance is closed to unity for T_A=900°C, and also because efficiency is higher for T_A=900°C than for T_A=800°C, one could conclude that the ferrite $Ni_{0.5}Zn_{0.3}Co_{0.2}Fe_{1.98}O_{4-x}$ should be retained, after annealing at T=900°C. But if bandwidth should be favored, instead of efficiency, then the recommended annealing temperature for the same ferrite material should be T_A=800°C, and not 900°C. As a counterpart the reduced impedance is then Z/Z_0=0.73, far from unity. Then it appears that the value of annealing temperature of a given material influences deeply its electromagnetic properties, and therefore the ability of the antenna to be used at given frequency.

Interest in using half-massive ferrites as substrates for antennas miniaturization, instead of bulk materials, lies in the easiness to tailor their electromagnetic properties, in particular through the value of the applied temperature during heat treatment.

TABLE I
PATCH ANTENNA CHARACTERISTICS FOR SAMPLE 2 (T_A=800°C)

	f=0.4GHz	f=0.8GHz	f=1GHz
n	4.54	4.28	4.62
Z/Z_0	0.73	0.75	0.77
W (mm)	82.6	43.81	32.46
Bandwidth	12.5 %	10.2 %	15.9 %
Efficiency	9.87 %	16.3 %	13.7 %

TABLE II
PATCH ANTENNA CHARACTERISTICS FOR SAMPLE 3 (T_A=900°C)

	f=0.4GHz	f=0.8GHz	f=1GHz
n	5.26	5.75	5.64
Z/Z_0	1.03	1.13	1.11
W (mm)	71.3	32.6	26.6
Bandwidth	7.3 %	18.6%	33.7 %
Efficiency	16.1 %	13.4 %	9.44 %

The case of patch antenna with W=71.3mm was simulated over sample S3 (T_A=900°C) with HFSS software. The reflexion coefficient is presented in Figure 5: it exhibits a resonance frequency of 397 MHz with a bandwidth of 29.5 MHz (7.4%). These results agree with those of Table 3 (F_0 = 400MHz – BP = 7.3%).

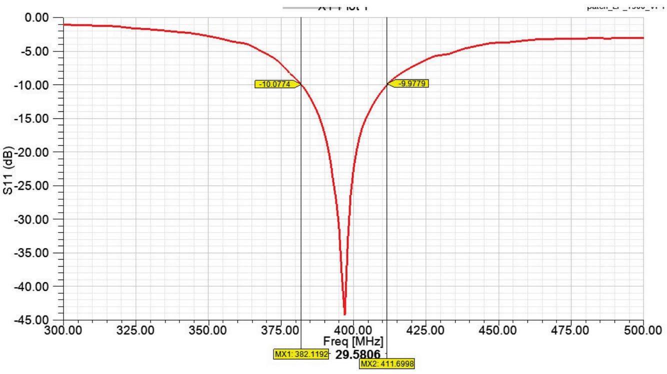

Fig.5. Reflexion coeffcient for a patch antenna (width W=71.3mm) printed over sample S3 (T_A=900°C) of thickness d=3mm.

IV. CONCLUSION

$Ni_{0.5}Zn_{0.3}Co_{0.2}Fe_{1.98}O_{4-x}$ ferrites were synthetized and annealed at various temperatures T_A. Depending on the value of annealing temperature T_A, the obtained half-massive ferrite ceramics (with porosity fractions ~50% in volume) shows competitive electromagnetic properties in the range of frequency up to 1GHz. Patch antennas realized with these half-massive ferrites as substrates were considered. It was shown that the value of annealing temperature for a given material affects deeply its electromagnetic properties, and therefore it influences the ability of the antenna to be used at given frequency: antennas performances (bandwidth BW and radiation efficiency η), calculated through numerical means, and through compact expressions as well, are sensitive to T_A. The value that must be selected for T_A depends on which one among the two antenna parameters considered in this study has to be favored (BW or η). In the field of the present study, T_A=800°C is a good choice for application up to 0.8GHz, whereas T_A=900°C leads to better results at frequencies below 0.5GHz. Interest in using half-massive ferrites as substrates for antennas miniaturization, instead of bulk materials, lies in the large facility to tailor their electromagnetic properties, in particular through the value of the applied temperature during heat treatment.

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